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A Comparison of Rain-Related Phosphorus and Nitrogen Loading from Urban, Wetland, and Agricultural Sources

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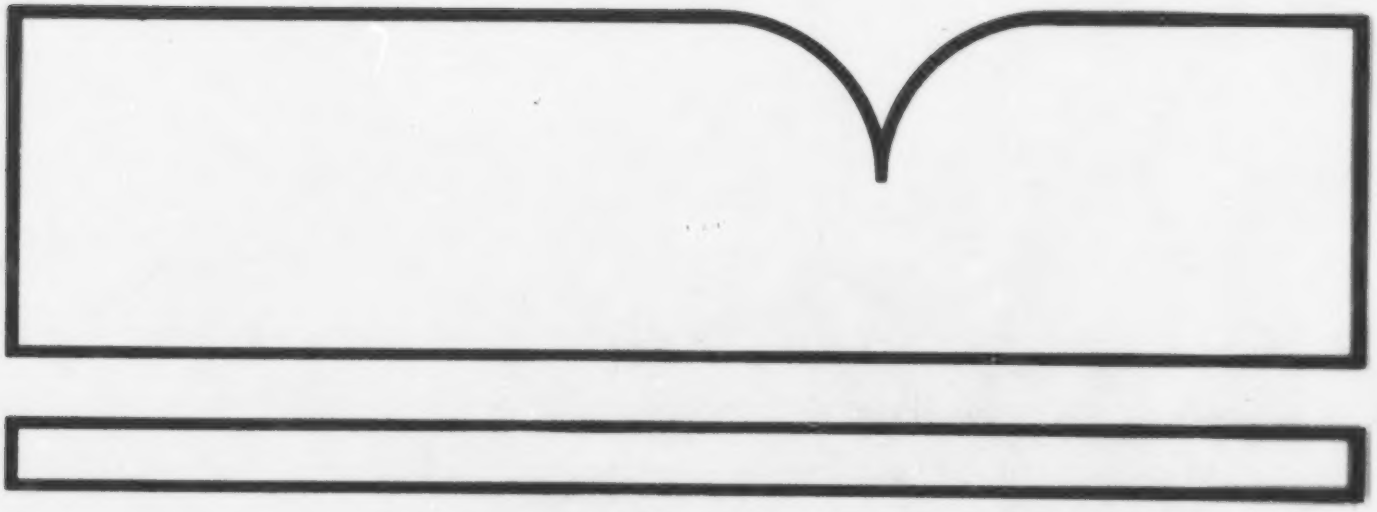

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16. ABSTRACT

Comprehensive watershed studies have been conducted for two lakes located in the Lake Michigan drainage system. Studies were conducted from March through October of 1979. During that interval, large differences in storm-related nutrient loading were measured from urban, wetland, and agricultural sources. Eliminating runoff due to melt of the snow pack, it was found that rain-related discharge from the urban area studied was 0.578 kg total-P and 3.688 kg total-N ha^{-1} of watershed. RAin induced runoff from marshes in the same drainage basin transported 0.023 kg total-P and 0.585 kg total N ha^{-1} of catchment. Rainfall of approximately the same amount caused runoff from agricultural land of 0.180 kg total-P and 5.965 kg total-N ha^{-1}. Algae of both lakes were phosphorus limited;nitrogen was present in excess. Using constants from Nichols-Dillon relationships in the literature regarding phosphorus, phytoplankton biomass, and secchi disc transparencies, the urban input of phosphorus ha^{-1} of drainage was sufficient to bring 0.96 ha-m of lake water to undesirable algal bloom status. Similarly, marsh input ha^{-1} would bring an estimated 0.04 ha-m into bloom. By the same calculation, storm-related agricultural runoff would result in 0.30 ha-m of lake water becoming undesirably rich in algae. Knowing the number of hectares in these types of catchment and the volume available in a particular lake for phytoplankton production, decisions regarding cost-effective treatment of rain-related discharge can be made.

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A COMPARISON OF RAIN-RELATED PHOSPHORUS AND NITROGEN LOADING FROM URBAN, WETLAND, AND AGRICULTURAL SOURCES

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Abstract—Comprehensive watershed studies have been conducted for two lakes located in the Lake Michigan drainage system. Studies were conducted from March through October of 1979. During that interval, large differences in storm-related nutrient loading were measured from urban, wetland, and agricultural sources. Eliminating runoff due to melt of the snow pack, it was found that rain-related discharge from the urban area studied was 0.578 kg total-P and 3.688 kg total-N ha^{-1} of watershed. Rain induced runoff from marshes in the same drainage basin transported 0.023 kg total-P and 0.585 kg total-N ha^{-1} of catchment. Rainfall of approximately the same amount caused runoff from agricultural land of 0.180 kg total-P and 5.965 kg total-N ha^{-1}. Algae of both lakes were phosphorus limited; nitrogen was present in excess. Using constants from Nichols–Dillon relationships in the literature regarding phosphorus, phytoplankton biomass, and secchi disc transparencies, the urban input of phosphorus ha^{-1} of drainage was sufficient to bring 0.96 ha-m of lake water to undesirable algal bloom status. Similarly, march input ha^{-1} would bring an estimated 0.04 ha-m into bloom. By the same calculation, storm-related agricultural runoff would result in 0.30 ha-m of lake water becoming undesirably rich in algae. Knowing the number of hectares in these types of catchment and the volume available in a particular lake for phytoplankton production, decisions regarding cost-effective treatment of rain-related discharge can be made.

INTRODUCTION

For a majority of lakes, the most important nutrient factors causing an increase in phytoplankton populations are phosphorus and nitrogen (Vollenweider, 1968). Consequently, a significant portion of the limnological literature has been devoted to the comparison of the annual export of phosphorus and nitrogen from different watershed types (Danigian & Crawford, 1977; Dillon & Kirchner, 1975; Colston, 1974). In general, the studies show that almost every constructional or agricultural activity on a watershed increases nutrient loading in drainage water. The urbanized watershed has been characterized as an outstanding exporter of nutrients (1.10–16.60 kg TP ha^{-1} yr^{-1}) to surface waters. While untreated sewage water contains the highest nutrient levels, urban storm water runoff alone typically exports nutrients at a rate well above that of other watershed types (Weibel, 1969). Urban fertilization of surface water diminishes valued supplies of suitable quality water for domestic and industrial purposes and frustrates attempts to meet the increased demands for recreational waters.

The potential of watershed runoff to maintain phytoplankton productivity in a receiving lake is largely determined by the level of nutrients exported throughout the summer when temperature and light regimes are optimal. A sustained nutrient input can maintain high productivity by replacing particulate phosphorus and nitrogen sedimented throughout the season (Wetzel, 1975). Annual loading estimates from watersheds in the seasonal north temperate region are often dominated by quantities carried in a spring pulse of discharge. For this reason, annual estimates tend to mask the degree of loading to a lake during the period of stratification.

In this paper, we examine phosphorus and nitrogen losses from marshland, urban, and agricultural watersheds with an emphasis on rain induced loading. This component of surface drainage is used as a means of comparing the watershed types with respect to the ability to maintain phytoplankton productivity in a lake throughout the summer.

STUDY AREAS AND METHODS

Lake Lansing, Ingham County, MI has a low relief watershed of approx. 842 ha. Runoff from approx. 776 ha of the watershed moves to the lake through adjacent marshes and enters the lake through 6 discrete surface streams. Street drains carry runoff from approx. 2.5 ha of residential and commercial areas in the watershed.

Skinner Lake, Noble County, Indiana receives runoff from a rolling agricultural watershed of 3813 ha. Runoff characteristics were determined from data collected from the Rimmel stream which carries water to the lake from approx. 3090 ha of the watershed.

Discharge of each marsh stream to Lake Lansing was measured three times per week from the onset of flow (5 March 1979) to cessation (8 June 1979). Discharge rates of four of the streams were determined with standard use of a Pigmy-type Gurley current meter. Rectangular weirs were installed across the remaining two streams and discharge was calculated by applying stage height readings to U.S.G.S. approximation formulae (USDI, 1967).

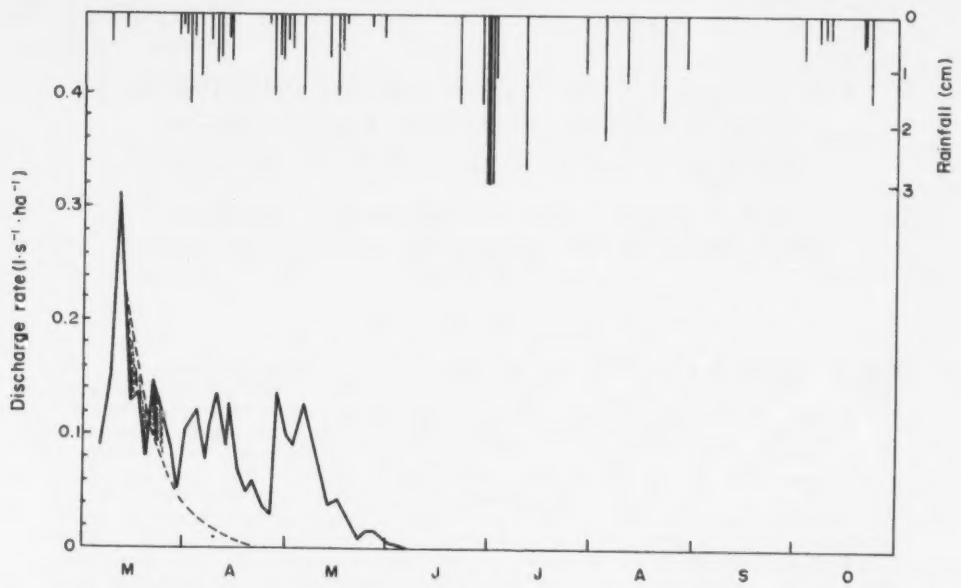

Fig. 1. Normalized hydrograph for the summed discharge of 6 streams draining marshland (c. 776 ha) in the Lake Lansing watershed and the record of rainfall for the interval March through October of 1979.

Water samples were collected from each stream each time discharge was measured and aliquots were composited according to a discharge-proportional scheme devised to reduce the number of samples to be analyzed from 36 (6 stream samples × 3 collections per week × 2 weeks) to 6 (one 2-week discharge-proportional composite per stream). Central to the compositing scheme was the idea that each sample (e.g. collected at time t_1) represented the volume of water discharged during the time interval extending from halfway to the previous sample collection ($t_1 - t_0/2$), to halfway to the following sample collection ($t_2 - t_1/2$). This method accounts for the possibility of detecting changes in water quality resulting from an observed change in discharge.

If the frequency of measurement is high relative to the rate of fluctuation in flow, we can assume a linear change from one measured discharge value to the next. The volume of water discharged represented by the sample collected at t_1 (shaded area in the illustration) can be calculated:

$$V = \frac{Q_0 + 3Q_1}{8}(t_1 - t_0) + \frac{3Q_1 + Q_2}{8}(t_2 - t_1),$$

where V = the volume of water discharged, and Q_0 = the discharge rate measured at time 0 (t_0). An aliquot from a water sample representing twice the volume of discharge as that of a second sample would be twice as large. Discharge proportional aliquots were added to a composite for intervals of 2 weeks, after which the composite was analyzed for total phosphorus and total nitrogen. "Running" composites were acidified (2 ml conc. H_2SO_4 l^{-1}) and refrigerated. Six composite samples (1 per marsh stream) were submitted to the laboratory biweekly.

During the interval of interest, beginning on 5 March, the urban drains of the Lake Lansing watershed discharged only during rain events. Relationships between total urban drain discharge and amount of rainfall were determined by plotting the total volume of discharge against the corresponding amount of rainfall for each of several monitored storms. The total volume of water discharged was calculated from periodic measurements of the discharge rate of each drain throughout the monitored storm. Weirs were installed to facilitate the measurement of discharge rates. Water samples collected during the beginning, middle, and end of each monitored storm were composited according to a discharge-proportional scheme analogus to that described for the marsh stream samples. The total amount of rainfall was read from a rain gage set at Lake Lansing.

Discharge of the Rimmel stream in the Skinner Lake watershed was measured daily from 2/23/79 to 4/15/79 with use of a Gurley current meter. Water samples, collected each time discharge was measured, were composited and stored in the same manner as those collected from the Lake Lansing watershed. After 4/15, discharge was measured at 2-week intervals and grab samples were returned to the laboratory for immediate analysis. Rainfall data were obtained from an automatic precipitation recorder located near the lake.

Total phosphorus concentrations were determined colorimetrically using the single reagent-ascorbic acid method on unfiltered, persulfate-digested samples.

Total nitrogen is defined as the sum of the nitrate–nitrite and total Kjeldahl nitrogen. Nitrate–nitrite nitrogen was determined colorimetrically by the cadmium reduction method. Total Kjeldahl nitrogen was determined colorimetrically after digestion and distillation of an unfiltered sample. All values are reported as P and N (APHA, 1975).

RESULTS

The summed discharge rates of the 6 marsh streams that empty into Lake Lansing reached a maximum of 257 $l s^{-1}$ on 3/9/79 and fell to zero by 6/13/79 (cf. Fig. 1). Early spring fluctuations in the marsh hydrograph correspond to freezing temperatures on 3/11 and from 3/14 to 3/16, and thawing temperatures on 3/19. Thereafter during the spring, the fluctuations in

Table 1. Total and rain induced loading* of total phosphorus and total nitrogen from marshland in the Lake Lansing watershed (1979)

Interval of measurement	Total discharge ($m^3 \times 10^{-4}$)	($m^3 ha^{-1}$)	Total phosphorus (kg)	(kg ha^{-1})	Total nitrogen (kg)	(kg ha^{-1})
3/5–3/16						
Total	13.4	170	10.5	0.013	166.1	0.214
Rain	Nil	—	—	—	—	—
3/17–3/30						
Total	10.8	140	5.7	0.007	134.8	0.174
Rain	3.1	40	1.6	0.002	38.2	0.049
3/31–4/13						
Total	11.6	150	7.9	0.010	141.1	0.182
Rain	9.4	120	6.4	0.008	114.2	0.145
4/14–4/27	7.0	90	4.3	0.006	95.9	0.123
4/28–5/11	9.7	130	4.8	0.006	164.5	0.212
5/12–6/8	2.4	30	0.4	0.001	43.1	0.056
3/5–6/8						
Total	54.9	710	33.6	0.043	745.5	0.961
Rain	31.6	410	17.5	0.023	455.9	0.585

* Rain induced loading = total loading after 4/13.

the discharge rate of the marsh correspond to wet and dry periods. During the interval from 3/5 to 3/16 the runoff coefficient (i.e. m^3 of observed discharge/m of rainfall × m^2 of catchment area) was 1.73, indicating that snow melt was contributing to the observed discharge. From 4/28 to 5/11 the runoff coefficient was 0.36, and from 5/11 to 6/8 the coefficient fell to 0.09.

The peak discharge of 257 l s^{-1} resulted from the melting snow pack. Separation of runoff due to snow melt from that due to rain events was done by describing the expected recession from a discharge of 257 l s^{-1} had there been no spring rain. It was assumed that the expected stream flow recession can be characterized by those segments of the hydrograph that were undisturbed by rainfall (Barnes, 1940; Davis & DeWeist, 1960). By isolating dry weather hydrograph segments (e.g. from 5/4 to 5/11 of Fig. 1), the undisturbed recession could be described by:

$$Q = (a)(1.14)^{-t}.$$

If the recession curve described by this equation is applied to the peak discharge of 3/9, then:

$$Q = (257)(1.14)^{-t}.$$

where Q is the discharge in l s^{-1}, and t is the number of days beyond 3/9. This analysis allows for the separation of total discharge into the component associated with water collected over winter and that induced by spring rain and enables a more meaningful comparison of rain induced runoff between watersheds.

The occurrence of freezing temperatures in the middle of March caused the discharge rate to fall below that expected from the recession curve. This was followed by a warming trend and a spike in discharge; in spite of a lack of rainfall. The area under the curve, between the observed and expected rates of discharge, from 3/10 to 3/16 was used to estimate the volume of water held back by freezing temperatures. This volume of retained water is considered to be a part of the discharge associated with meltwater (cf. stippled areas of Fig. 1).

Total phosphorus and total nitrogen content in composited water samples was used with separated components of marsh discharge to yield estimates of nutrient export from the marsh (Table 1). The intervals of measurement correspond to compositing intervals. Estimates of loading of TP and TN were divided by the number of hectares of watershed to normalize the data for comparison. During the entire period of flow, the marsh released a total of 0.043 kg TP ha^{-1} and 0.961 kg TN ha^{-1}. Of that, 0.023 kg TP ha^{-1} and 0.589 TN ha^{-1} was released as a result of rainfall during the period.

A comparison of the total discharge from the urban drains during monitored events and the corresponding amount of rainfall reveals two distinct relationships, one associated with the wet spring season and another with summer and fall (Fig. 2).

The correlation coefficient (r^2) between urban drain discharge and spring rainfall was 0.78, and the relationship can be described by:

$$V = 14.25 + 7.05x$$

where V is the total volume of discharge from a spring storm and x is the corresponding amount of rainfall in mm. The discharge–rainfall relationship in the summer and fall reflects a lower runoff coefficient of 0.96, and is described by:

$$V = -6.45 \pm 4.73x.$$

Variable soil moisture conditions in vegetated portions of the urban catchment preceding a given rainfall may account for some variation within each relationship.

The linear description of the spring relationship was applied to the local rainfall record from 3/5 to 6/8 to estimate the volume of urban drain discharge. The

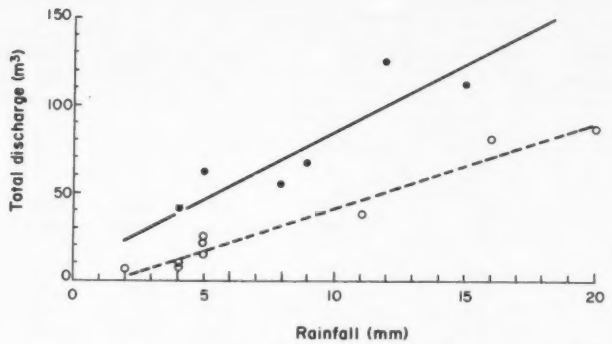

Fig. 2. Relationship between rainfall and summed discharge from urban (street) drains emptying into Lake Lansing in the spring (——) and summer–fall (– – –) periods of 1979.

summer–fall relationship was applied to the amount and occurrence of rainfall in the interval from 6/9 to 10/22 (Table 2).

Total phosphorus and total nitrogen content in composite samples collected during monitored events averaged 0.547 mg TP l^{-1} and 3.494 mg TN l^{-1} with one standard deviation of 0.149 and 1.120 respectively. There was no statistically significant difference (α0.05) between the elemental concentrations in spring and summer–fall samples. The average TP and TN levels of all samples were used with urban drain discharge to calculate nutrient export.

For the entire season under consideration (3/5 to 10/22), the per ha loading of TP was 25 times the rain induced marsh loading. Urban drains carried nearly 6 times the rain induced TN loading from the marsh.

The discharge hydrograph of the Rimmel stream in the Skinner Lake watershed shows a dramatic elevation in discharge rate during the first week in March and falls to a stable flow by the middle of May (Fig. 3). Separation of the Rimmel hydrograph was done in a manner similar to that of the marsh hydrograph. Dry weather segments (e.g. 4/12 to 4/15) were considered in order to describe the expected rate of recession of discharge in the absence of rainfall. The expected decay of the discharge rate from the level observed on 3/6 can be described by:

$$Q = (1.25)(0.74)^t,$$

where t is the number of days after 3/6.

TP and TN concentrations in composited samples were used with separated components of discharge to calculate nutrient export from the agricultural land (Table 3). The rain induced loading over the 2/23 to 10/22 interval was 0.180 kg TP ha^{-1} and 5.965 kg TN ha^{-1}.

In summary, the normalized rain induced loading from 2/23/79 to 10/22/79 in kg ha^{-1} was:

$$\text{TP: } 0.023_{(\text{marsh})} < 0.180_{(\text{agriculture})} < 0.595_{(\text{urban})}$$

$$\text{TN: } 0.585_{(\text{marsh})} < 3.802_{(\text{urban})} < 5.965_{(\text{agriculture})}.$$

Table 2. Rain induced loading of total phosphorus and total nitrogen to Lake Lansing from urban street drains (1979)

Interval of measurement	Total discharge (m^3)	Total discharge ($m^3 ha^{-1}$)	Total phosphorus (kg)	Total phosphorus (kg ha^{-1})	Total nitrogen (kg)	Total nitrogen (kg ha^{-1})
3/5–3/16	57	23	0.031	0.012	0.199	0.080
3/17–3/30	209	84	0.114	0.046	0.730	0.292
3/31–4/14	343	137	0.188	0.075	1.198	0.479
4/14–4/27	224	90	0.123	0.049	0.782	0.313
4/28–5/11	329	132	0.180	0.072	1.149	0.460
5/12–6/8	430	172	0.235	0.094	1.502	0.601
6/9–6/23	129	56	0.076	0.030	0.486	0.194
6/24–7/8	437	175	0.239	0.096	1.526	0.610
7/9–7/23	132	53	0.072	0.029	0.461	0.184
7/24–8/8	142	57	0.078	0.031	0.496	0.198
8/9–8/23	143	57	0.078	0.031	0.499	0.200
8/24–9/7	42	17	0.023	0.009	0.147	0.059
9/8–9/29	0	0	—	—	—	—
9/30–10/14	76	30	0.042	0.017	0.265	0.106
10/15–10/22	18	7	0.010	0.004	0.063	0.025
3/5–6/8	1592	638	0.871	0.348	5.560	2.225
3/5–10/22	2721	1090	1.489	0.595	9.503	3.802

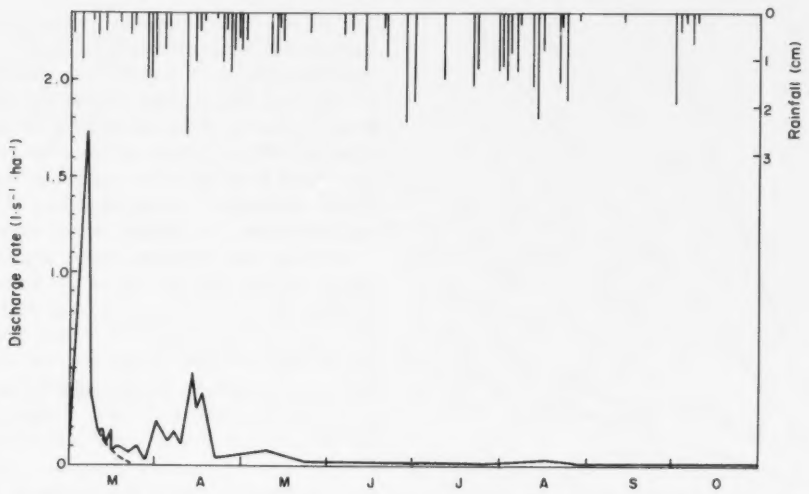

Fig. 3. Normalized hydrograph for the Rimmel stream draining agricultural land (approx. 3090 ha) in the Skinner Lake watershed and the record of rainfall for the interval March through October of 1979.

DISCUSSION

In comparison, the marshland discharge had the lowest capacity to support phytoplankton productivity throughout the summer based on the low level of total nutrient contribution and the early-summer termination of discharge. By contrast, the urban and agricultural watersheds exported roughly 10 times the nitrogen and phosphorus in sustained loading throughout the summer and fall. The significance of this nutrient loading can be given perspective by examining the potential impact on populations of phytoplankton in a receiving lake.

Other studies of nutrient levels in surface waters have shown that phosphorus concentrations are generally the phytoplankton yield-limiting factor (Edmondson, 1972; Schindler, 1974). As a result, a number of empirically defined relationships between measured phosphorus and the abundance of phytoplankton in lakes have been reported (Dillon &

Table 3. Total and rain induced loading* of total phosphorus and total nitrogen from agricultural land in the Skinner Lake watershed (1979)

Interval of measurement	Total discharge ($m^3 \times 10^{-5}$)	($m^3 ha^{-1}$)	Total phosphorus (kg)	($kg\ ha^{-1}$)	Total nitrogen (kg)	($kg\ ha^{-1}$)
2/23–3/6						
Total	11.2	362	478	0.155	8362	2.705
Rain	4.6	150	198	0.064	3468	1.122
3/7–3/31						
Total	11.1	358	285	0.092	9313	3.013
Rain	3.5	114	90	0.029	2957	0.957
4/1–4/15	9.6	311	170	0.055	7613	2.463
4/16–4/30	3.2	103	21	0.007	1295	0.419
5/1–5/14	2.6	84	20	0.006	1291	0.418
5/15–5/28	0.9	30	8	0.002	310	0.100
5/29–6/12	0.5	15	2	0.001	136	0.044
6/13–6/25	0.4	14	1	0.000	179	0.058
6/26–7/9	0.4	14	3	0.001	245	0.079
7/10–7/23	0.4	13	4	0.001	110	0.035
7/24–8/5	0.5	15	1	0.000	81	0.026
8/6–8/20	0.8	25	14	0.005	348	0.113
8/31–9/6	0.8	27	8	0.003	96	0.031
9/7–9/25	0.9	29	6	0.002	177	0.057
9/26–10/13	0.9	28	10	0.003	128	0.041
2/23–10/13						
Total	44.2	1428	1031	0.333	29556	9.602
Rain	30.0	972	556	0.180	18306	5.965

* Rain induced loading = total loading after 3/31.

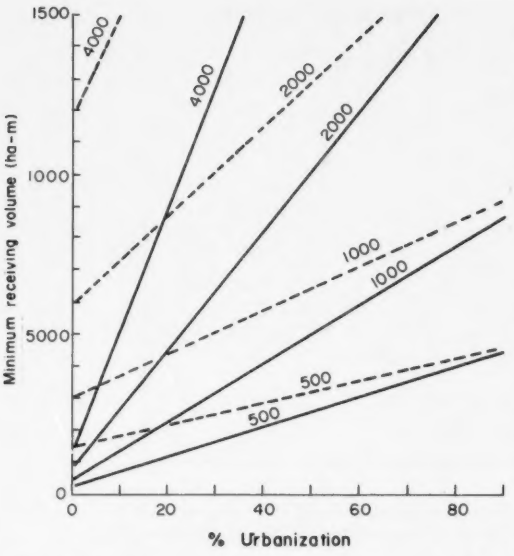

Fig. 4. The minimum volume of phosphorus limited lake water that would be brought to an undesirable phytoplankton density by urbanizing marshland (——) or agricultural land (– – –) according to the data of this study. Numbers on lines indicate selected marsh and agricultural drainage areas in hectares.

Rigler, 1974). They are intended for use as predictive tools. Through an examination of the available literature, Nichols & Dillon (1978) have found that the most well defined relationship is that between summer total phosphorus concentration in the euphotic zone of a lake and the average summer phytoplankton cell volume. The relationship between these variables is linear and can be described by:

$$\text{phytoplankton cell volume} = 0.21x - 2.6,$$

where x is the total phosphorus concentration in mg m^{-3}, and the cell volume is expressed in $\text{mm}^3\,\text{l}^{-1}$. Nichols and Dillon further present a well defined relationship between cell volume and resultant secchi disc visibility. This relationship was shown to be non-linear, and can be generally described by:

$$\text{secchi disc visibility} = (3.20)\,(1.08)^{-x},$$

where x is the phytoplankton cell volume and secchi disc visibility is expressed in meters.

Using these relationships and selecting a measure of nutrient-related water quality that is undesirable, for example a secchi disc transparency of 1.5 m or less, the impact of nutrients discharged to lakes from urban, marsh, or agricultural land can be predicted. The Nichols–Dillon relationships are such that at a secchi disc measurement of 1.5 m, the predicted volume of phytoplankton cells would be near $10\,\text{mm}^3\,\text{l}^{-1}$. This corresponds to a total phosphorus concentration of $60\,\text{mg m}^{-3}$.

If this level of phytoplankton density is chosen as an index of minimum acceptable water quality, then by our data the rain induced total phosphorus loading from one hectare of marshland would be sufficient degrade 0.04 ha-m of phosphorus limited lake volume to that level. By the same calculation, the discharge from one hectare of the agricultural watershed would adversely affect 0.30 ha-m of lake. By contrast, summer runoff from the urban watershed would debase 0.96 ha-m, roughly 3 times the impact of the agricultural watershed and 24 times that of the marshland.

Assuming that watershed export of phosphorus increases linearly with the size of the watershed, comparisons like these can be used to predict the impact on a lake that would occur if a watershed were converted from one type to another. For example, our export estimates from marsh, agricultural, and urban areas were used with the Nichols–Dillon relationships and the criterion that a secchi disc transparency of 1.5 m or less constitutes undesirable nutrient-related water quality, to predict the volume of phosphorus limited lake water adversely impacted by urbanizing either marsh or agricultural land. The result is shown in Fig. 4.

Figure 4 shows that for a given watershed area, the volume of receiving water adversely impacted (minimum receiving volume) increases to an upper limit as urbanization is increased towards 100%. In approaching the upper limit, the figure suggests that a given increase in urbanization of marshland would cause a greater change over previous conditions than would the same increase in urbanization of agricultural land.

While our data are site specific to a degree, the technique has general applicability. The approach can be used as a basis for decisions regarding cost effective treatment of existing rain-related discharges, or decisions regarding the need for treating discharges from urban developments during the planning stages of those developments.

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